EO-1 Advanced Land Imager Stray Light Analysis and Impact on Flight Data

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Abstract - The EO-1 Advanced Land Imager (ALI) was developed under NASA's New Millennium Program. The ALI is validating new technologies and measurement techniques for application to future wide field-of-view, non-cryogenically cooled, pushbroom earth observing systems. Extensive pre flight measurements of the BRDF for the optical elements were made. These data were used in a system level analysis to assess the impact of stray light on flight observations. A model was developed to estimate the error in measured scene radiance as a function of the ratio of scene radiance to background radiance. This effect can be significant for scenes with high contrast. A quantification of the ALI stray light characteristics based on preflight measurements and flight observations will be presented. The impact of stray light on the radiometric accuracy of in-flight data will be compared to the model.

INTRODUCTION

The EO-1 Advanced Land Imager is the primary instrument on the first Earth Observing Mission (EO-1) of NASA's New Millennium Program (NMP). The objective of NMP missions is to flight validate key technologies which could lead to significant improvement in performance and reduction in cost for future missions. Technology validation, in general, must be accomplished in the context of some science or other user application. For EO-1, the measurement objectives were directed towards Landsat data continuity. The measurement requirements were developed from the bottom up by the instrument team and in collaboration with the earth science community. The primary ALI Performance goals were to meet or exceed key Landsat-7 performance (w/o thermal band) [1,2]. All other performance goals were, in general, guided by Landsat-7. One such secondary goal was the sensor system stray light rejection performance.

Optical fabrication priorities were to first produce mirrors with correct figuring to achieve the required image sharpness over the full 15 x 1.3 degree field of view. Mirror finish was lower on the priority list. The SiC mirrors produced by SSG Inc. for the ALI were of excellent figure quality but constrained by EO-1 programmatic considerations (budget, schedule) in obtaining optimum BRDF performance [3,4]. Based on mirror BRDF measurements performed by SSG Inc. and Schmitt Measurement Systems and analysis by Lambda Research Corp. [5], the EO-1 SiC mirrors did not meet the EO-1 adopted Landsat 7 specification for scattered light. It was concluded by the EO-1 project office [3,4] that the ALI telescope mirror surface quality was reasonably good and comparable to other Earth sensing instruments and that the full set of NMP technology validation objectives for ALI were realizable without additional mirror polishing. Lincoln Laboratory proceeded with integrating the ALI and performed a thorough instrument system calibration.

A separate NASA funded technology program was conducted by SSG Inc., which demonstrated component level BRDF consistent with the Landsat 7 stray light specification. Silicon clad SiC aspheric optics and uncoated SiC flat optical surfaces were demonstrated to have BRDF, which met all requirements. Multiple optics were demonstrated, including a full scale, ALI spare primary mirror.

STRAY LIGHT MODELING

A methodology for assessing the effect of telescope stray light on the measurement of scene radiance was developed. It was based on a generalization of the Stray Light Analysis Report No. 3 by Lambda Research [5]. The analysis also included the effects of the reflective baffle, which defined the aperture stop, at the secondary mirror. The black paint used on the baffle was Aeroglaze Z-306. The stray light contribution from this effect amounted to 1%. The results provide a useful and simple tool for estimating the effects of stray light.

Assumptions:

1. The scene geometry is the same as for the Landsat specification, consisting of a large annular background region surrounding a small circular target region.
2. The scattered background radiance falling into the target region is due to both mirror scatter [5] and scatter from the reflective baffle. The major contribution from mirror scatter comes from approximately 3 degrees around the target region. The contribution from the black reflective baffle is defined as 1% of a 3 degree background region, centered on the target.
3. The fraction of background radiance falling into the target region is a constant.

4. The fraction of target radiance that is scattered out is also a constant and is the total integrated scatter (TIS) from the referenced report.
5. The radiometric calibration is based on a very low spatial frequency standard, e.g., a large extended near field source.

Definitions:

L_B = The true background radiance
L^*_B = The estimated background radiance
L_T = The true target radiance
L^*_T = The estimated target radiance
ΔL_T = The uncalibrated target radiance error due to the telescope stray light
ΔL_B = The calibrated background radiance error due to the telescope stray light
σ_B = The fraction of background radiance falling into any target region
σ_T = The total fraction of radiance that is scattered from any portion of the scene

The resulting radiance errors are:

$$\Delta L_B = L^*_B - L_B = 0$$
$$\Delta L_T = L^*_T - L_T = [\sigma_B / (1 - \sigma_T + \sigma_B)]\ [L_B - L_T]$$
$$\Delta L_T / L_T = \varepsilon\ [L_B / L_T - 1.]$$

Table 1
Stray Light Parameters

Band	σ_T(%)	σ_B(%)	ε(%)
Pan	6.5	3.6	3.5
MS-1	15.5	7.6	8.3
MS-2	10.9	5.5	5.8
MS-3	7.6	4.1	4.2
MS-4	4.4	2.7	2.7
MS-5	0.9	1.3	1.3
MS-7	0.5	1.2	1.2

Stray light may be an issue for measurements on dark scenes near very large and very bright regions and conversely for small bright scenes surrounded by large dark regions. This is especially true at the shorter wavelengths. The on-orbit effects of stray light on the ALI have been quantified and the results are summarized in this paper.

ON-ORBIT STRAY LIGHT CHARACTERIZATION

Two types of data have been used to characterize the ALI stray light performance on-orbit: limb scans and nominal Earth scenes containing uniform regions. The limb scans were used to evaluate the off-axis scatter of the ALI mirrors and black paint. The Earth scene data were compared to Landsat 7 ETM+ and ground truth data to evaluate the impact of stray light for a variety of scene contrasts.

Limb Scan Observations

The off-axis stray light characteristics of the ALI have been investigated by scanning the Earth's limb across the telescope field of view. Four limbs scans were performed in 2001, scanning in the +pitch, -pitch, +roll, -roll directions. For each observation, the instrument begins collecting data with the Earth completely filling the ALI FOV. The instrument is then pitched or rolled until the Earth's limb is 50° off-axis and the ALI is viewing deep space. A plot of an individual detector's response over time traces the transition from Earth observing to space observing events. The Earth limb profile for a +roll scan as viewed by detector 100 for Band 3 is depicted in Figure 1.

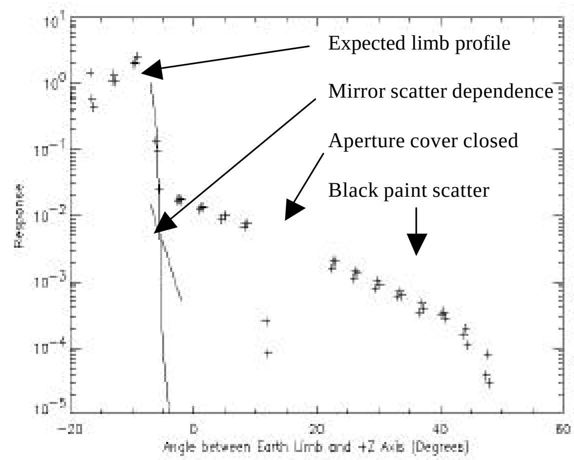

Fig. 1. Earth limb scan history for detector 100, Band 3.

The Earth's limb is located at the -7° position (angle of the detector FOV relative to the boresight). An instrument with zero stray light effects will observe a limb profile that is the product the limb's natural illumination falloff with altitude and the instrument edge spread function. The expected limb profile is overlaid in Figure 1. The effects of stray light are evident for angles up to 40 degrees off-axis. Also overlaid in Figure 1 is the expected limb profile for the ALI based on the stray light analysis of the mirrors conducted by Lambda Research Corporation [5]. Clearly, the expected falloff due to stray light effects from the mirrors alone does not match the observed profile. This data confirms the effects of scatter from the Z306 black paint inside of the telescope. These data are also useful for they define the angular dependency of all ALI stray light sources in the +pitch, -pitch, + roll, and - roll directions.

Earth Observations

The impact of stray light for typical Earth scenes and the validity of the stray light model discussed previously have been evaluated by comparing diffuse scenes as seen by the ALI, the Landsat 7 ETM+, and ground truth data. EO-1 and Landat 7 are flying in formation, allowing for data from the same scene to be collected by the ALI and ETM+ with only a one-minute separation. The ground truth data are collected during both observations.

For the comparison, the radiance of a spatially uniform region of a scene is extracted from the ALI, ETM+, and ground truth data. The ratios of the ALI data to similar ETM+ data (bands 1, 2, 3, 5, 7) and ground truth data are then plotted as a function of the *radiance ratio*, t/b. The *radiance ratio* is calculated from the ETM+ data and is defined as the ratio of the mean target radiance to the mean background radiance, defined by a circle 3° in radius and centered on the target region. In this context, the *radiance ratio* is defined as the *true* contrast of the region being evaluated for stray light effects.

The predicted impact of stray light on the ALI data as a function of t/b for Band 3 is provided in Figure 2. For regions where the target radiance is greater than the background radiance, the expected stray light error is –3% and is dominated by the effect of light being scattered out of the target region into the surrounding background region due to the effects of total integrated scatter. For targets whose radiance is much lower than the mean background radiance, the impact of stray light is the result of light being scattered from the bright background into the dim target regions.

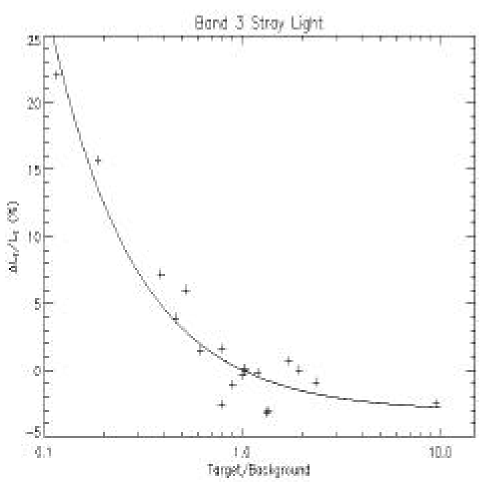

Fig. 2. Stray light model and flight data for Band 3.

Also plotted in Figure 2 is the result of an ALI, ETM+, and ground truth comparison for scenes containing a variety of t/b values. The scenes used for this analysis included Maricopa, Arizona, Suez Canal, Antarctic Ross Ice Shelf, Cuprite, Nevada, Barreal Blanco, Argentina, and the San Francisco Salt Ponds.

The model and data agree qualitatively and indicate a substantial rise in the expected radiometric error for targets with low radiance ratios for this band (3). This analysis was extended to also assess the effects of stray light for Bands 1, 2, 5 and 7 (these ALI bands are very similar to the corresponding ETM+ bands). The results for Bands 1, 2, and 3 are shown in Figure 3. The derived values of the scattering parameter ε, for all the bands, are summarized in Table 2.

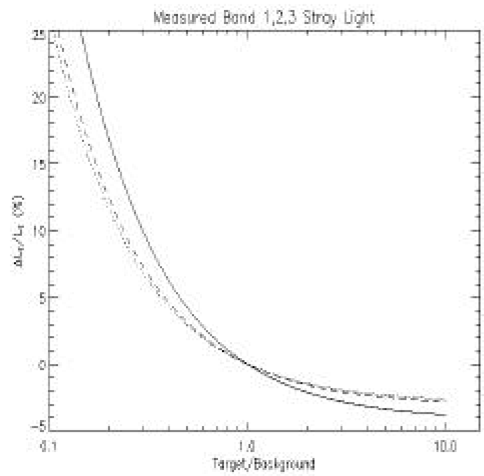

Fig. 3. Effects of stray light for bands 1 (solid), 2 (dotted), 3 (dashed). These results have been derived by fitting the stray light model to flight data.

Table 2
Radiance errors derived from the stray light model and flight data.

Band	Radiance Error ε (%) Theoretical	Radiance Error ε (%) Measured
1	8.3	4.2
2	5.8	2.9
3	4.2	3.1
4	2.7	-
5	1.3	<1.0
7	1.2	<1.0

The SWIR stray light data suggest little impact for all radiance ratios t/b > 0.75. However, it must be noted that the stray light analysis could not be extended below t/b = 0.75 due to the large scatter in the ALI and ETM+ data as a result of low signal in these bands. Significant error due to stray light is expected and observed for SWIR data with t/b < 0.75 (e.g. small lakes). The data and model also indicate an increasing effect of stray light with decreasing wavelength, particularly for t/b < 1.0. However, the flight data suggest the magnitude of the stray light impact is less than predicted by the model for the VNIR bands (Table 2).

IMPACT ON FLIGHT DATA

In principle, the effects of stray light on a particular target could be assessed if the radiance ratio for the target was known. However, the effects of large off-axis scattering by the black paint on the interior of the telescope cavity can be problematic in some instances. As an example of the utility of the stray light model and the effects of the black paint scatter, a scene of the West Coast of Africa is shown in Figure 4.

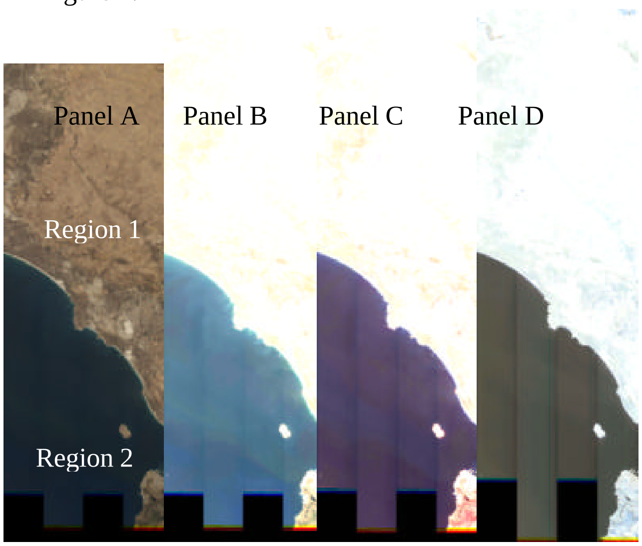

Fig. 4. Stray light impact example for West Coast, Africa scene. The effects of black paint scatter in the water is evident in the enhanced images in panels B, C, D.

Panel A of Figure 4 is a true-color, Band 321, image that has been radiometrically calibrated. Regions 1 and 2 have radiance ratios near 1.0 and so the predicted radiometric error due to stray light is minimal. Panels B, C, and D are three-color images defined by bands 321, 432, and 755p respectively. These images have been stretched to enhance the region of water off the African coast. Although the radiometric model predicts minimal stray light in this region, clear 3-10% SCA-to-SCA banding is evident. The stray light effects observed off the African coast are the result of large off-axis angle scattering of the in-land region photons off the black-paint behind the secondary mirror. To properly account for this effect, a second background region, extending more than ten degrees, would be needed. Since the ALI field of view is only 3 degrees, an independent measure of the extended background radiance is required.

Finally, it should be noted that extended off-axis scattering by the black paint only becomes problematic for large regions with relatively low radiances. This is because the scattering effect of the paint is approximately 1% of the mean of the extended background. For small regions (< 3°) the model discussed above is appropriate. For larger regions, the effects of the black paint scatter are small if the target radiance approaches or exceeds the extended background radiance. However, for large regions with low radiance levels (e.g. water) and a relatively high-extended background radiance (e.g. land, clouds, ice), the stray light model breaks down and the 1% scatter effect of the black paint becomes significant.

CONCLUSION

The EO-1 Advanced Land Imager stray light has been characterized on orbit using Earth limb scans and by comparing flight data to ETM+ and ground truth data. The stray light model agrees qualitatively with the flight data for off-axis angles < 3°. The stray light component caused by the black paint lining the inside of the telescope is the dominant source of stray light for larger off-axis angles and is difficult to assess using only ALI data.

For scenes with high contrast (e.g. coastlines, lakes in snow covered areas, mostly cloudy scenes over water) the impact of stray light on the ALI radiometry may become significant. It is therefore recommended that scientific inferences, developed using high contrast ALI data, should be carefully evaluated for stray light effects.

REFERENCES

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[3] eo1.gsfc.nasa.gov/Technology/StrayLightIssues.html

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This work was sponsored by NASA/Goddard Space Flight Center under U.S. Air Force, Contract F19628-00-C-0002.